Superconducting Nanowire Single-Photon Detectors

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JPL team & collaborators

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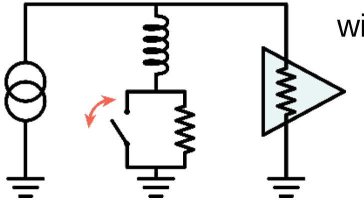
  - Marty Stevens
  - Adriana Lita
- MIT: Karl Berggren
- Commercial:
  - PhotonSpot
  - Quantum Opus

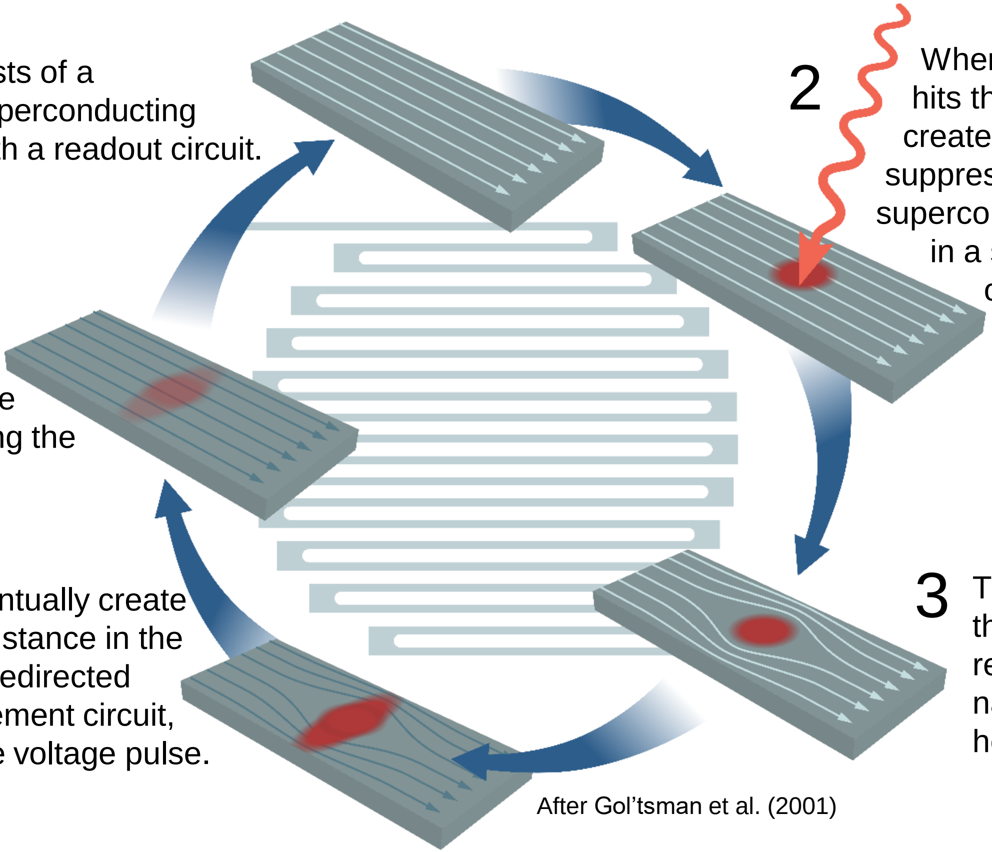
SNSPDs: background

SNSPDs: basic operation

detection process



1 An SNSPD consists of a current-biased superconducting wire in parallel with a readout circuit.



2 When a photon hits the wire, it creates a hotspot, suppressing the superconductivity in a small region of the wire.

3 The current flowing through the resistive region heats the nanowire and the hotspot grows.

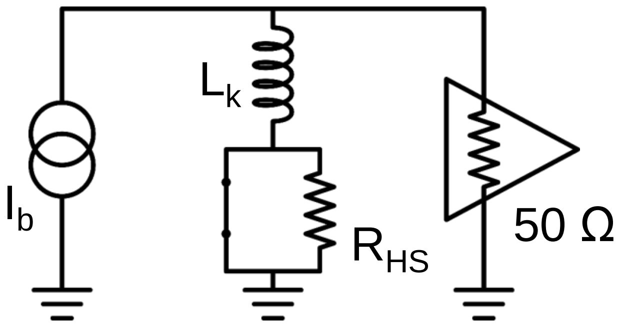
4 The hotspot can eventually create 10s of kOhms of resistance in the wire. The current is redirected through the measurement circuit, creating a detectable voltage pulse.

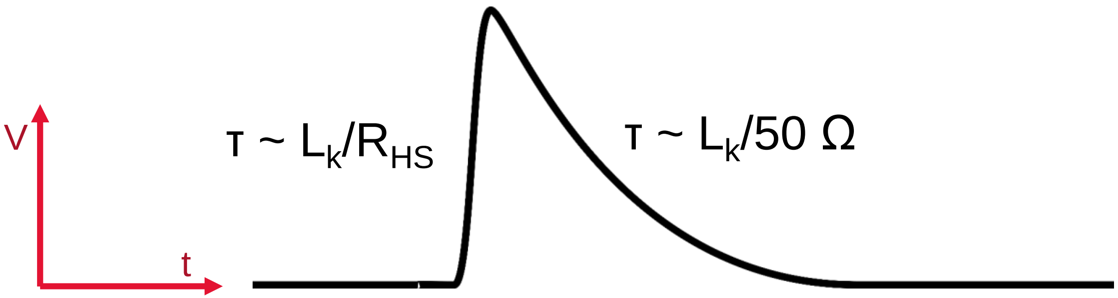
5 With the current through the nanowire reduced, the hotspot cools off, returning the wire to its original state.

After Gol'tsman et al. (2001)

SNSPDs: basic operation

Electrical model



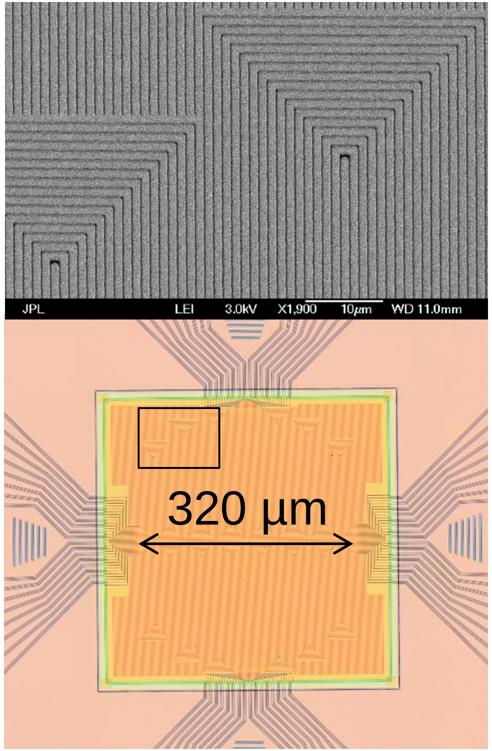


- Dead time is set by the thermal relaxation time of the hotspot or the electrical decay time
- Longer/thinner/narrower wires = more Lk = slower

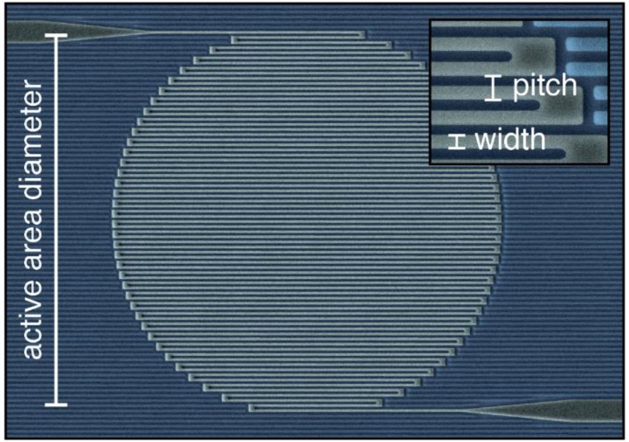
SNSPDs: geometry

- Wire widths ~ 100 nm
- Wire thicknesses ~ 5-10 nm
- Wires can be patterned to fill any desired area
- Directionality of meander pattern leads to polarization sensitivity

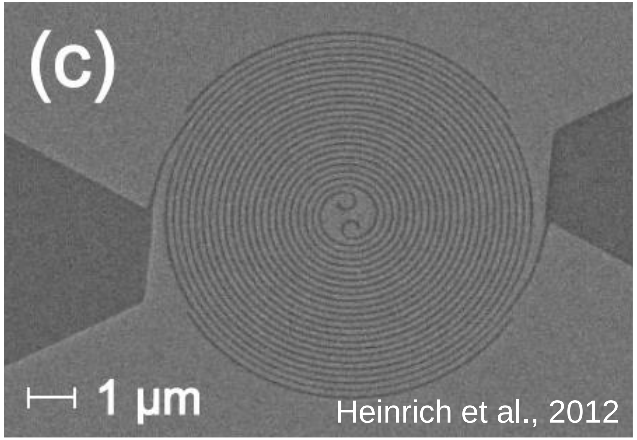
64 channel quad array
w/ cowound wires



Fiber-coupled single pixel; meander



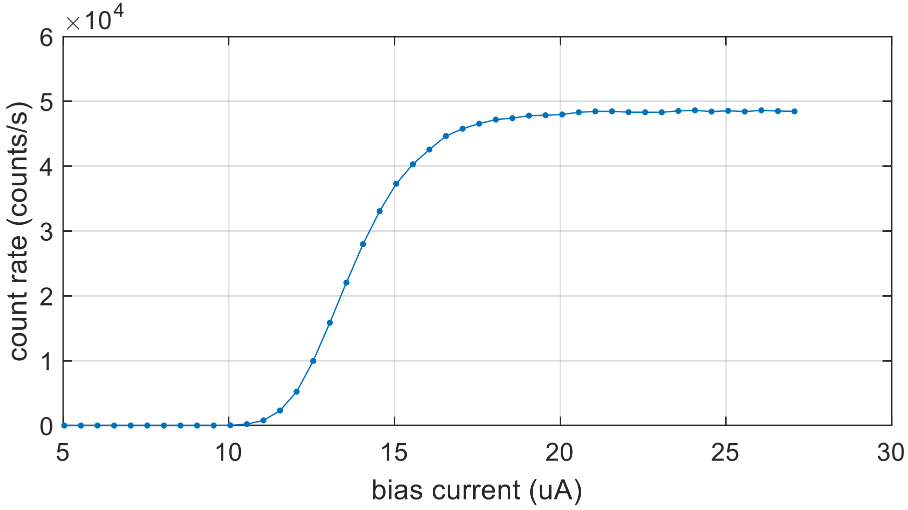
Fiber-coupled single pixel; spiral



SNSPDs: basic operation

Internal efficiency saturation

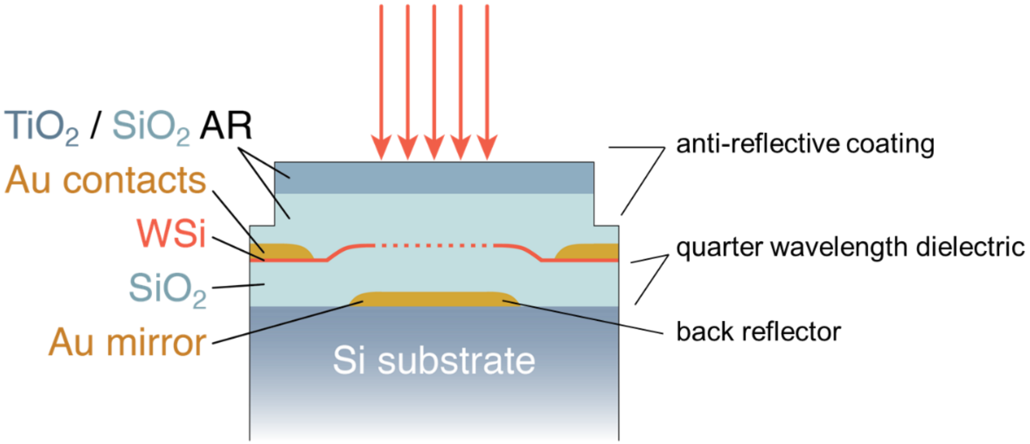
- The larger the current flowing through the wire, the higher the probability that a photon will produce a click
- For an optimized nanowire, at sufficiently high currents, every photon that is absorbed in the nanowire produces a click (i.e., the internal QE = 1)
- This behavior is evident by a plateau in curves of efficiency or count-rate vs. bias current



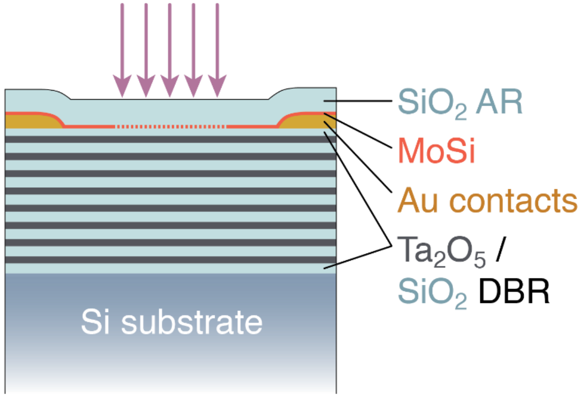
SNSPDs: Enhanced efficiency

Optical stack

- Only 5-30% of light is absorbed in bare wires deposited directly on a silicon substrate
- To enhance absorption, anti-reflective coatings and back mirrors are used



Near-IR stack



Near-UV stack

SNSPDs: Near-IR performance

Efficiency

- System detection efficiency defined as percent of photons entering cryostat detected by SNSPD
- 93% fiber coupled,1550nm
- 75% free space, 1550nm

Dark Counts

- 1e-4 cps in NIR SNSPDs
- Probably limited by noisy electronics

Max Count Rate

- 20 Mcps / pixel (WSi)
- > 1 Gcps on array

Time Resolution

- ~3 ps FWHM, specialized NbN device
- 80 ps FWHM, 64-pixel WSi array
- 25 ps FWHM, 64-pixel WSi array w/ 2-end readout

Active Area

- 320 µm 64-pixel array
- 10-50 µm single pixel
- 64-pixel “row-column” scalable imaging array demonstrated
- Kilopixel “row-column” array fabricated

Operating Temperature

- 1.2 K WSi 1550 nm
- >10 K MgB2, needs significant additional technology development

Current applications

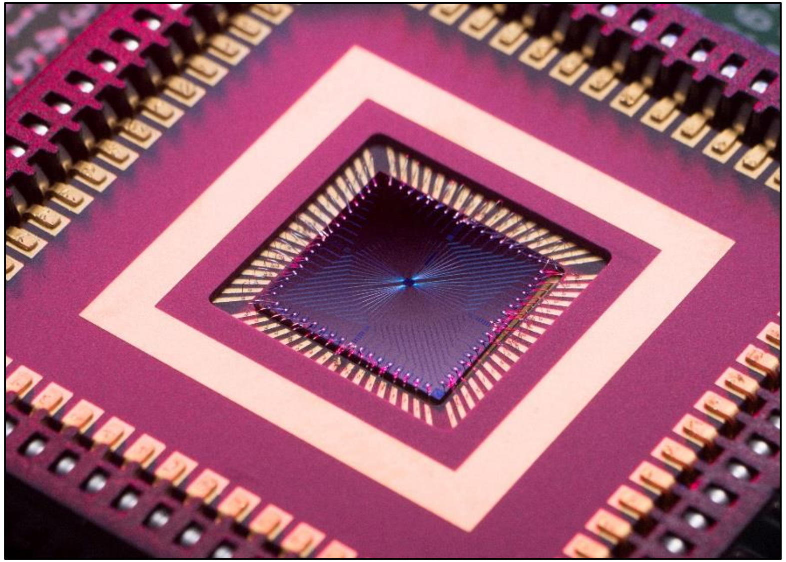
- Optical communication (DSOC, LLCD)
- Quantum information (QKD, trapped ion QIP, tests of fundamental physics)
- LIDAR
- CMOS fault detection
- Fluorescence microscopy

Future performance & development path

Development necessary for mid-IR astronomy

The following need to be demonstrated with SNSPDs:

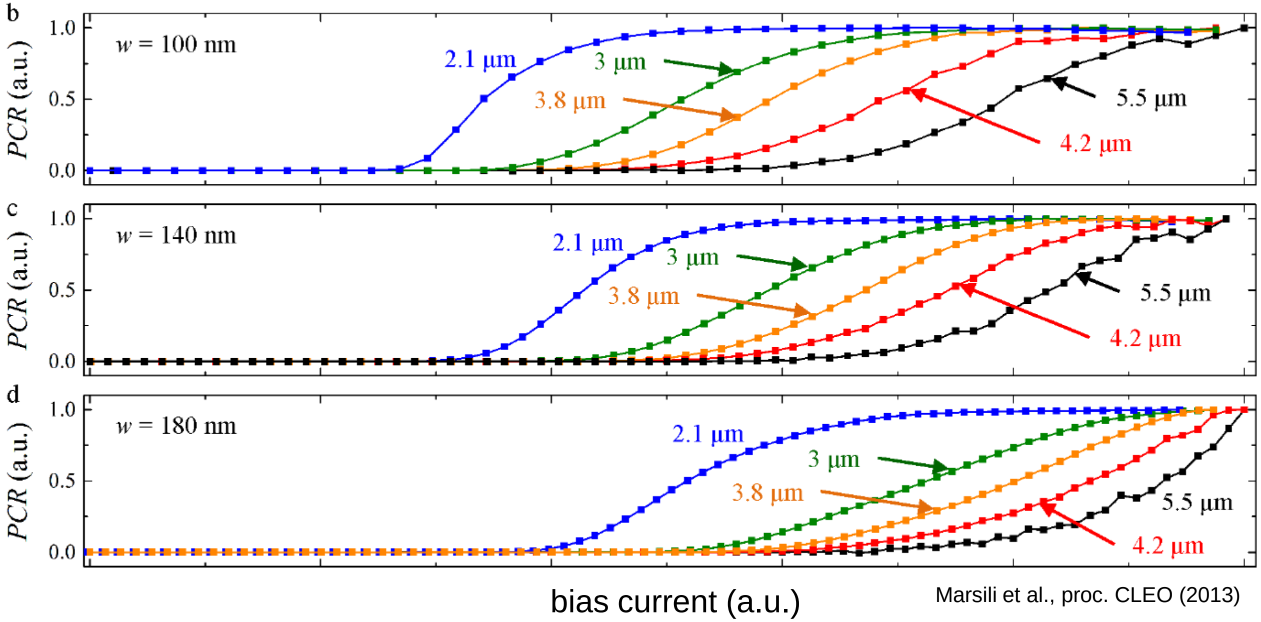
- Mid-IR single-photon sensitivity
- High mid-IR efficiency
- Stability
- Large-format arrays
- Flight compatibility (i.e. radiation tolerance, long-term robustness, yield)



Mid-IR single-photon sensitivity

Current status

- Single photon sensitivity demonstrated out to 10 µm
- Saturated efficiency demonstrated to 5.5 µm (right)
- Cutoff current is higher for longer wavelengths

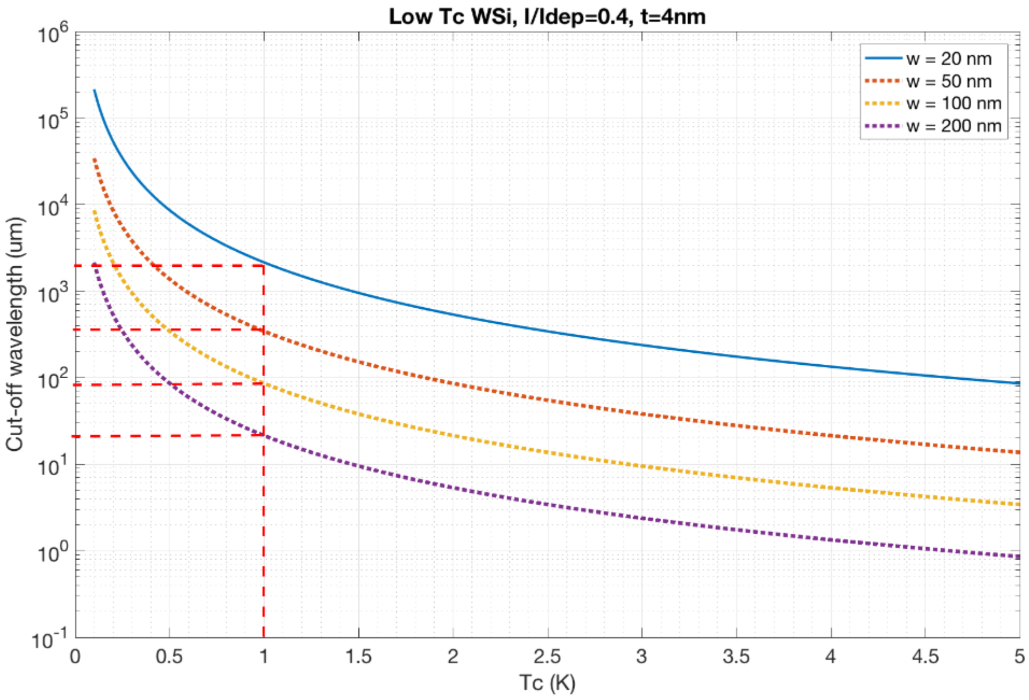


Marsili et al., proc. CLEO (2013)

Mid-IR single-photon sensitivity

Predicted performance

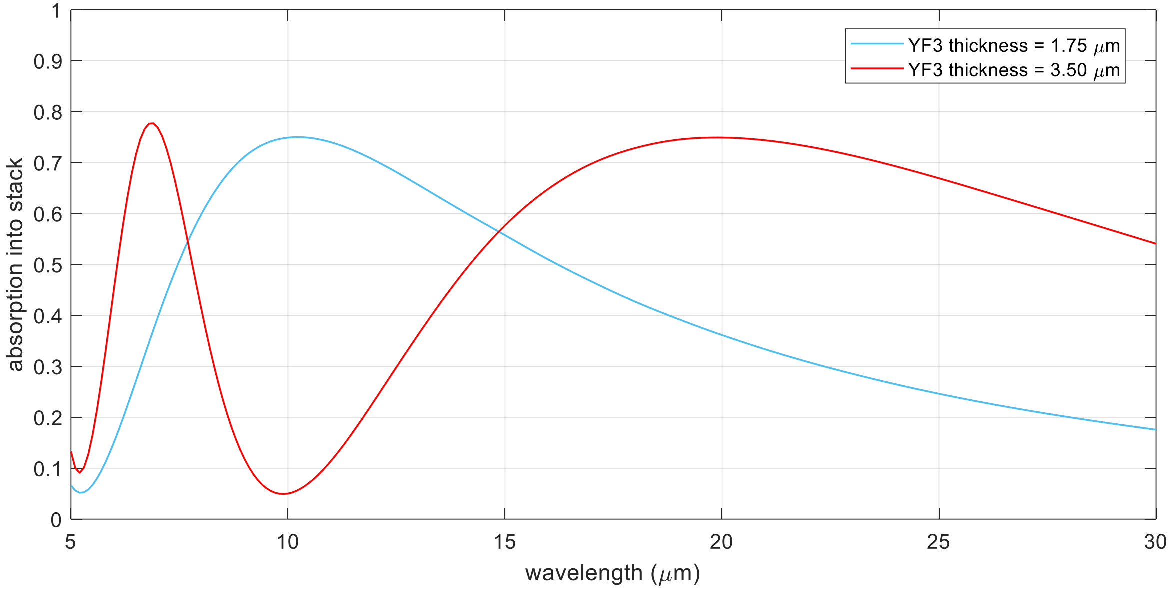
- Decreasing the wire cross-section or critical temperature make the nanowire sensitive to longer wavelengths
- Nanowires down to 20 nm have been fabricated, but narrow wires have lower yield
- According to models of WSi nanowires, 100 nm wires should be sensitive to 30 µm light at temperatures below 1 K, while 50 nm wires should be sensitive to 30 µm light above 1 K



High mid-IR efficiency

- Need to identify materials for MIR optical stacks
- Low index: YF3
- High index: ZnSe, ZnS, (aSi?)
- Index of refraction of WSi is very high at MIR wavelengths – not well-matched to air
- Explore multi-layer SNSPDs to increase absorption, decrease polarization dependence

preliminary RCWA model:



Broadband design: absorption > 50% (for polarized light) using two optical stack designs

High mid-IR efficiency

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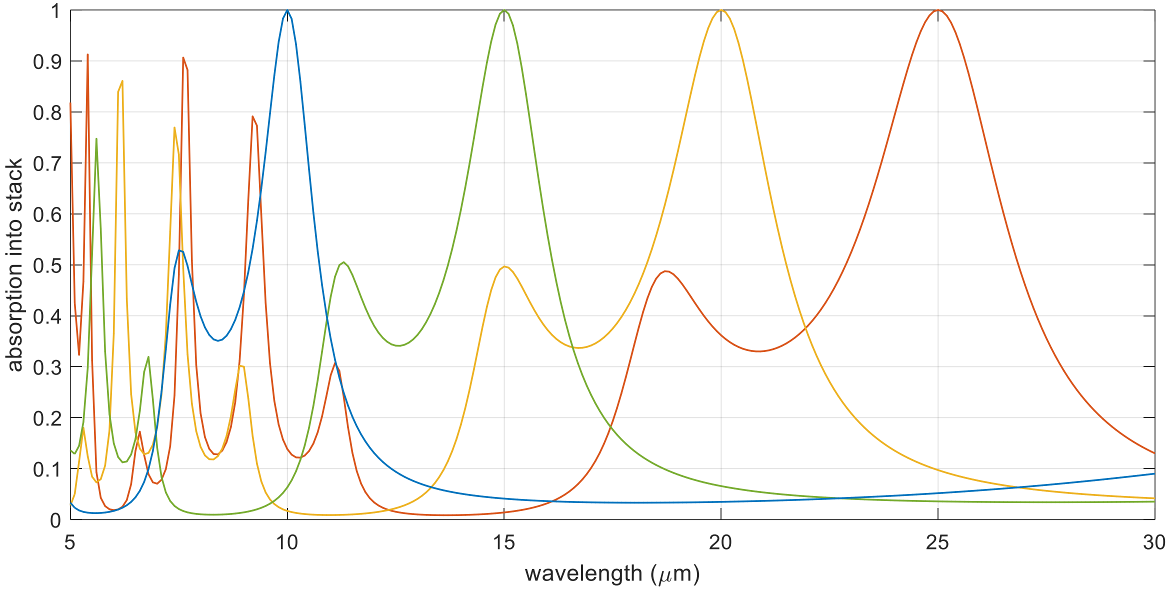

Narrowband design: absorption > 90% (for polarized light) for narrow range of wavelengths

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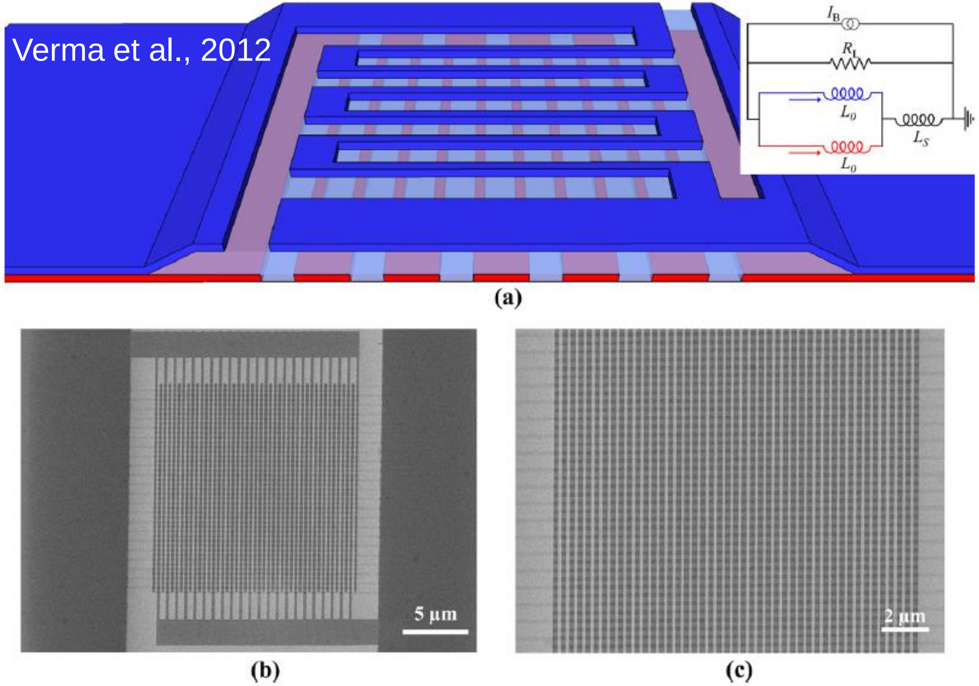
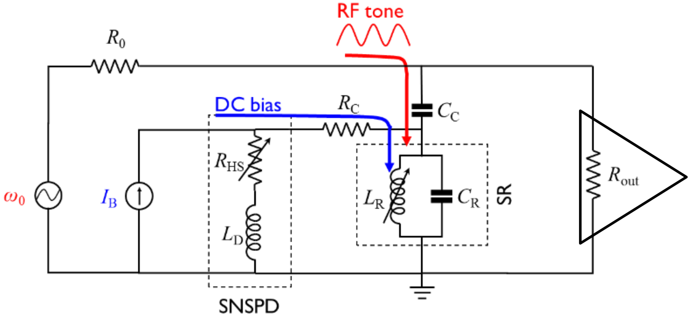


Detector stability

- SNSPDs are likely to have high stability:
  - Signal out of detector is digital – immune to amplifier drifts
  - Efficiency plateau – immune to drifts in bias current & temperature
  - The intrinsic dark count rate is somewhat current and temperature dependent, but as the iDCR is < 1 mHz/pixel, any small changes in the DCR will not affect the signal at the ppm level
- Currently trying to find best way to measure stability. Initial measurements show stability of a few 10s of ppm over a couple of hours, but shot noise level was ~10 ppm, and drifts in source polarization were not controlled for and could have had a large effect.

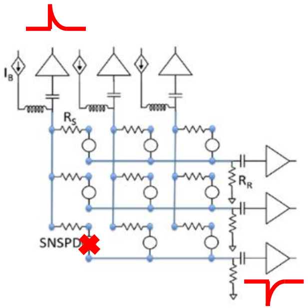
Multiplexing for large-format arrays

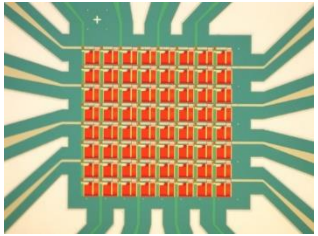
Frequency Domain (16)



- Similar trade space to MKIDs

Row-Column (64)

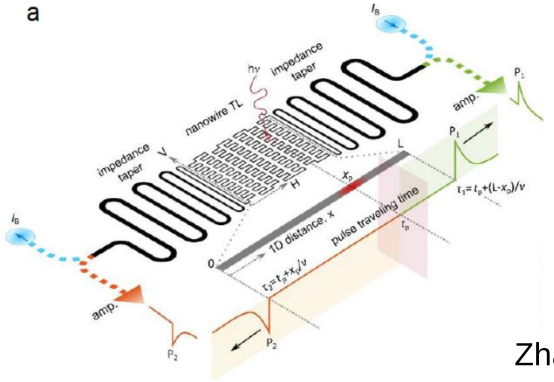




Allman et al., 2015

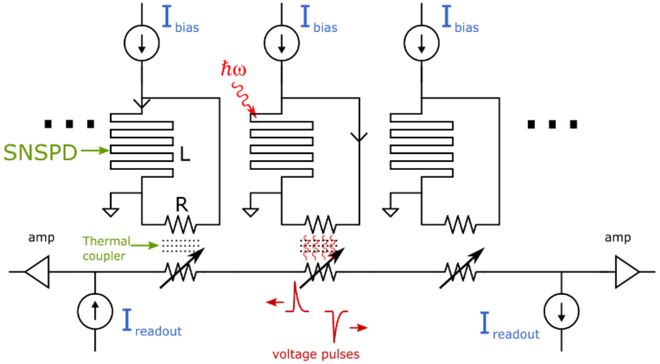
- NxN array read out with 2N readout lines

Position Sensitive Nanowire (500)



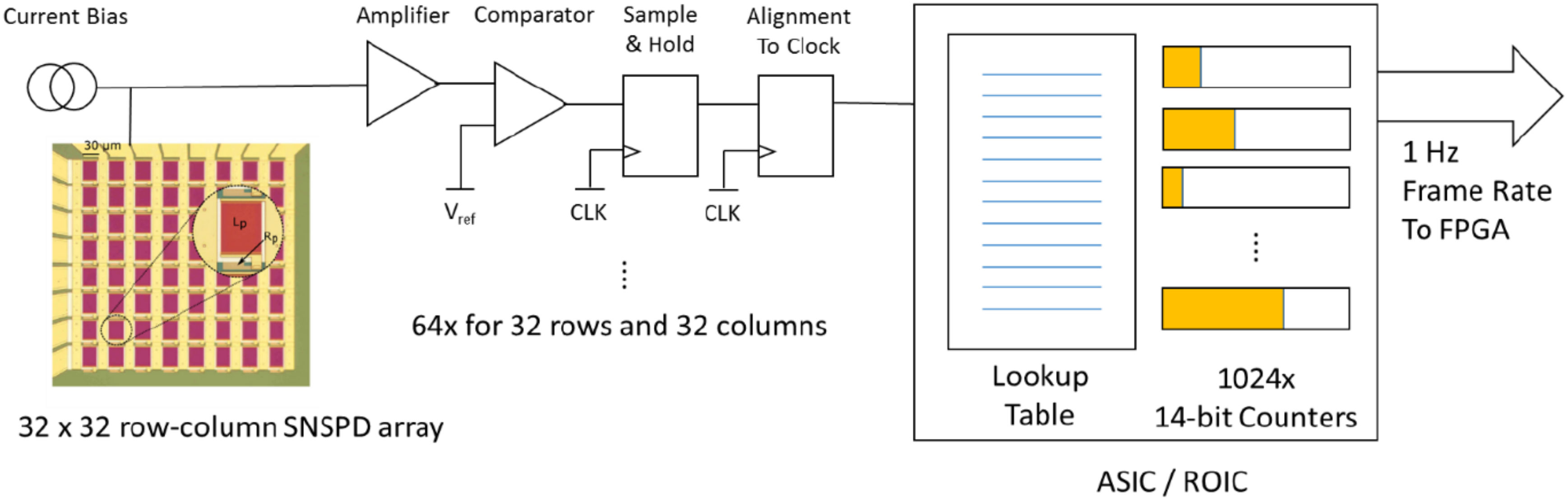
Zhao et al., 2016

Thermally Coupled Imager (0)



Multiplexing for large-format arrays

Readout scheme



Summary of challenges

Challenge	Approach	Notes
Demonstrate sensitivity past 7 um	Make narrower wires and test with far-IR sources	Have small amount of internal funding; applied for ROSES funding w/ NIST
Design high-efficiency optical stacks	Characterize materials in mid-IR and identify dielectrics that meet requirements	This would also be covered by ROSES proposal
Demonstrate larger arrays	Currently fabricating 32x32 row-col arrays to use with existing 64-channel readout	Area of active pursuit by multiple SNSPD groups. NIST has submitted second ROSES proposal on this topic
Demonstrate SNSPD stability	Measure existing near-IR arrays with existing 64-channel readout	Applied for internal JPL funding to perform initial measurements.

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